FPGA-BASED DIGITAL CONTROLLER FOR DC-DC CONVERTER

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ABSTRACT

This thesis presents a FPGA-based digital controller for a DC-DC converter. The converter topologies chosen in this project is Non-Inverting Buck-Boost converter. The main difference from DSP-based solution is that FPGA allows simultaneous execution of all control procedures. The control algorithm has been developed using Verilog language based on the voltage control loop. The FPGA switching controller has been designed as simple as possible while maintaining the accuracy and dynamic response. The DE1 board is used to control the main circuit. Simulations and experimental results show the feasibility of the proposed method, opening interesting possibilities in motion and power electronics converter control.

ABSTRAK

Tesis ini membentangkan pengawal digit berasaskan FPGA untuk penukar DC-DC. Topologi penukar dipilih dalam projek ini ialah bilik menyongsang Buck-Boost penukar. Perbezaan utama dari penyelesaian berasaskan DSP ialah FPGA membolehkan pelaksanaan serentak semua prosedur kawalan. Algoritma kawalan telah dibangunkan dengan menggunakan bahasa Verilog berdasarkan gelung kawalan voltan. FPGA beralih pengawal telah direka semudah mungkin sambil mengekalkan ketepatan dan tindak balas dinamik. Papan DE1 digunakan bagi mengawal litar ini. Simulasi dan keputusan eksperimen menunjukkan kemungkinan kaedah yang dicadangkan, membuka kemungkinan yang menarik dalam gerakan dan elektronik kuasa kawalan penukar.

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LIST OF SYMBOLS AND ABBREVIATIONS

FPGA	-	Field-programmable gate array
VHDL	-	Very High Speed Integrated Circuit Hardware Description Language
PWM	-	Pulse Width Modulation
ADC	-	Analog-to-Digital Converter
SoPCs	-	System or Proxy Cache Server
PSIM	-	Physical Security Information Management
PLD	-	Programmable Logic Device
DSP	-	Digital Signal Processor
I/O PORTS	-	Input-Output ports
EMI	-	Electromagnetic Interference
ASIC	-	Application-specific Integrated Circuit
SiC	-	Silicon Carbide
PI	-	Proportional-Integral
PFC	-	Power Factor Correction
ESR	-	Equivalent Series Resistance
NIBB	-	Non-Inverting Buck-Boost

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

This chapter presents the introduction of the thesis including with a short overview of Non-Inverting Buck-Boost DC-DC converter and also introduction to FPGA. Furthermore, it details the purpose of the project, continuing with the objectives as well as the scope of the project and finishing with the outline of the thesis.

1.1 Introduction

Usually, power electronics circuits and systems have been controlled in industry using linear controllers combined with non-linear procedures such as pulse width modulation (PWM). [1].

The FPGA's are a reconfigurable digital logic devices which contain a variety of programmable logic blocks called Logic Elements (LEs) which can be configured using a Hardware Description Language (HDL). The main advantages of FPGA are wide parellism, deep pipelining, and flexible memory architecture. FPGAs show great potential for real-time hardware emulation, control applications, power electronics applications such as motor control, active power filters, predictive control algorithms, DC-DC power converters, or multilevel inverters. [1]

Non-inverting buck boost converters are capable of achieving a positive output voltage that is higher or lower than its input voltage. As battery powered devices are becoming more and more popular, this topology is becoming more attractive as it can make the use of the discharge cycles of a battery. When a battery input voltage is higher than its output voltage, a buck boost converter works in the buck mode of operation. In the buck mode operation, the converter decreases the input voltage to the necessary level for use at its output. When the battery input voltage is lower than the output voltage, the buck boost converter works in the boost mode of operation wherein the input voltage is increased to a level needed at output. It is relatively easy to implement the control in either pure buck mode of operation or a pure boost mode by leaving some power switches turned on or off.[2].

1.2 Objective of the Project

The intention of this research project is to develop a control system of Converter using Verilog language. In this case, the Non-Inverting Buck-Boost DC-DC Converter is the chosen topology for the converter for this research project. The requirement of this project is to keep the output voltage in stable condition even when the input are varies. The objectives of the research are:

a) to write a Verilog language to control the performance of the converter.

b) to construct and design a Buck-Boost converter with updated topology.

c) to demonstrate stability of output voltage using DE board as a controller.

1.3 Problem statement

It is well know that the digital control offers advantages over analog control. They own lower power consumption and enhanced reliability due to the lower number of components involved in the design. However, the digital control have specific constraints such as some design parameters such as algorithm delay will occur if high switching frequency are required.

Power electronics and drive usage are nowadays very sophisticated as this digital technology is of big interest since it allows implementing quite easily complex control strategies. Analog controllers despite their drawbacks such as parameter drifting or lake of integration, still remain the reference in terms of rapidity and bandwidth. That is the reason why digital controller execution times must be reduced while keeping the inherent flexibility of the chosen digital solution. This can only be achieved with the help of efficient digital platforms. Today, such digital platforms exist, some of them also integrate analog functions like Analog-to-Digital Converter (ADC) and they can be developed by the use of high performance design tools such as Field Programmable Gate Arrays (FPGAs). These components take benefits of a high integration rate. Furthermore, the recent FPGAs can be considered as real SoPCs since they can integrate high-performance processor cores and also, in some cases, ADCs. Thus, by using an FPGA-based controller, the designer is able to build a fully dedicated digital system that is perfectly adapted to the algorithm to implement.

1.4 Scope of project

The scope of this project is to design and implement FPGA-based controller for a DC-DC converter. In this case, the Buck-Boost converter were chosen.

1.5 Thesis Outline

This report is arranged and distributed into five chapters. Chapter 1 has presented a brief introduction of the project mainly about FPGA and the topologies of the converter, the problem statements, the objectives of the project and its scope, and the limitations identified using the proposed approach.

Chapter 2 of the dissertation includes a literature survey related to this project as per referred to previous studies and results obtained by past researchers. It also contains some important findings from past, researchers such as a review of existing database search algorithms presentations. Their respective advantages and disadvantages, with specific references.

Together with the literature review carried out in Chapter 2, has helped with the search for systolic array architecture that could potentially improve performance and cost. Chapter 3 provides a methodology in how this project is conducted in sequence.

Chapter 4 contains the results and findings of the project. A simulation is run on PSIM software and hardware performance are compared with the simulation results. Simulation result is analysed and studied.

Lastly is chapter 5 where this chapter concludes the dissertation. It presents a summary of research achievements together with a discussion of their significance. Some recommended future work also presented in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

FPGA is a short for ***F**ield-**P**rogrammable **G**ate **A**rray,* a type of logic chip that can be programmed. An FPGA is similar to a PLD, but whereas PLDs are generally limited to hundreds of gates, FPGAs support thousands of gates. They are especially popular for prototypingintegrated circuit designs. Once the design is set, hardwired chips are produced for faster performance.

Compare with DSP, FPGA has flexibilities in defining bit-width and I/O ports. Short bit width saves hardware resource and processing time. Long bit guarantees accuracy. Rich I/O ports mean FPGA-based system can be developed to control power electronics device requires more switching signals since one switching signal is generated by one port. Parallel processing makes FPGA have high efficiency. The design in FPGA is mapped into actual circuit and the processing is clock triggered. Precision will be better [4].

In terms of converter design, some of the research paper has been surveyed to choose the converter desired. V.D. Yurkevich*et al.*, [5] have design a controller for Buck-Boost converter using two controllers: the designed above inner switching controller and an outer continuous controller. The presented method of switching regulator design allows us to obtain the desired transients for buck-boost converter under uncertainty in model description and in the presence of unknown external disturbances.

Soft-switching Buck Boost converter using pulse current regenerative resonant snubber have been proposed by Y. Konishi and Y.F.Huang [8]. This type of Buck Boost converter has high reliability and simplicity of both the power circuit and control compared to the active methods. The passive regeneration snubber has a simple circuit configuration and wide operation region of the soft-switching action.

P. Olranthichachat, A. Saenthon and S. Kaitwanidvilai*et al*.[10], have suggested the Genetic Algorithm based fixed-structure H loop shaping control of a Buck Boost converter. H loop shaping control is an efficient method for designing a robust controller. This approach requires only a desired open loop shape in frequency domain. It was proved that the robust performance of the proposed controller is better than the conventional PI controller. It was valid and flexible as proposed in this paper. A new isolated bidirectional Buck Boost PWM converter as proposed by M. Delshad and H. Farzanehfard *et al*.[11], was using a simple PWM controller and it has minimum active switch in power stages.

Four switch Buck Boost converter was proposed by Marcos Orellana, Stephen Petibon, Bruno Estibals, and Corrine Alonso *et al*.[12], for photovoltaic DC-DC power applications. The switches were commute by two. The four switches (synchronous structure instead of asynchronous), increase the converter efficiency since the commutations are done very quickly compared to natural diode commutations. Nevertheless, the control must be done carefully in order to avoid short-circuits on the inductor and defective functioning. Its characteristics made it suitable for photovoltaic applications.

Ray-Lee Lin and Rui-Che Wang [13] has suggested a Non-Inverting Buck-Boost Power-Factor-Correction Converter with Wide Input-Voltage_range Applications. The Buck-Boost proposed in this research was non-inverting and the applications were wide due to the input-voltage range.

A Novel Method of Implementing Real-Time Buck-Boost Converter with Improved Transient Response for Low Power Applications was suggested by Boopathy, K [14]. It has the capability of skipping over higher loss interface stages such as buck–boost mode in the case of a real time buck–boost converter significantly improves the efficiency from 16% and 19% and ripple content has been reduced from 14 % to 4% of the circuit topology.

A research from Bo-Han Hwang [15], suggested an average-current-controlled techniques for a low-voltage Buck Boost converter. It can reduce some power management problems, such as size, cost, design complexity, simple compensation design, and EMI. The maximum efficiency was 72% at switching 1MHz frequency.Chin-Hong Chen [16] also had the same idea on controlling the Buck Boost by using the average-current mode controlled but the research was for the integrated non-inverting Buck Boost converter. It was only suitable for portable electronic applications and it can provide load current up to 300 mA.

There were some research that focused on controlling the converter using FPGA based [1], [2], [4], [5], [6]. Most of the research just focused on one basic topology such as just Buck and also Boost by itself. It has proven that the FPGA based controller have become one of the solution in controlling the converter. In overall, implementing the control algorithm in hardware description language (HDL) allows high flexibility and technology independence. The same controller can be directly synthesized into any other FPGA or even in an ASSIC, or it can also be added to other logic blocks forming a more complex multi-task system in single chip. Solutions based on specific hardware, that allows high concurrency, are suitable to be used in power electronics and motion control applications with nonlinear control approach like switching control in sliding mode does[1].

2.2 List of Paper Review

RESEARCHER (S)	TITLE	CONTROLLER METHODS	RESULT /ADVANTAGES
V. D. Yurkevich	Design Of Controller For Buck-Boost Converter	Closed-loop system with an inner switching controller and outer continuous controller.	Can obtain the desired transients for Buck-Boost converter under uncertainty in model description and in the presence of unknown external disturbances

Y. Konishi and Y.F. Huang	Soft-Switching Buck Boost Converter Using Pulse Current Regenerative Resonant Snubber.	Buck-Boost converter with soft-switching topology using a pulse current regenerative snubber circuit.	It has high reliability and the simplicity of both the power circuit and control compared to the active methods.
Vineeta Agarwal and Anupam Kumar	SiC Based Buck-Boost Converter	Buck-Boost converter using SiC diode CSD10060 and MOSFET (IRF-9530).	Recovery losses are very low as compared to that of the Si diodes due to the very low or negligible value of the reverse recovery current flowing through the SiC diodes as compared to the reverse recovery current flowing through the Si diode.
P. Olranthichachat, A. Saenthon and S. Kaitwanidvilai	Genetic Algorithm Based Fixed-Structure *H*∞ Loop Shaping Control Of A Buck-Boost Converter	Buck-Boost converter with current mode control requires only a desired open loop shape in frequency domain.	Controller has good robust performance and can be applied for the buck-boost converter and the proposed controller is better than that of the conventional PI controller.

M.Delshad, H.Farzanehfard	A New Isolated Bidirectional Buck-Boost PWM Converter	Converter was controlled by PWM signal and it have minimum active switch in power stages.	Power density of converter is high. Also this converter can operate buck-boost in either direction therefore it can operate under wide range variation of voltage source.
Marcos Orellana, StéphanePetibon, Bruno Estibals, Corinne Alonso	Four Switch Buck-Boost Converter For PhotovoltaicDc-Dc Power Applications	For switch Buck-Boost converter with four switches commute by two. The four switches increase the converter efficiency since the commutations are done very quickly compared to natural diode commutations.	Suitable for photovoltaic applications. High performance and the possibility of adaptation to different input and output time-varying voltage values.
Ray-Lee Lin and Rui-Che Wang	Non-Inverting Buck- Boost Power-Factor-Correction Converter With Wide Input-Voltage-Range Applications	Using a PFC controller L6562 and a high-side gate driver IR2117.	The proposed non-inverting buck-boost based PFC converter has both step-up and step-down conversion functionalities to provide positive DC output-voltage. Very high efficiency (90%).

Boopathy.KDr. BhoopathyBagan.K	A Novel Method Of Implementing Real-Time Buck Boost Converter With Improved Transient Response For Low Power Applications	Real Time Buck–Boost Converter. The Novel method is to add interface modes, which are a combination of buck and boost operating topologies.	Capability of skipping over higher loss interface stages such as buck–boost mode in the case of a real time buck–boost converter significantly improves the efficiency from 16% and 19% and ripple content has been reduced from 14 % to 4% of the circuit topology.
Bo-Han Hwang, Bin-Nan Sheen, Jiann-Jong Chen, Yuh-Shyan Hwang and Cheng-Chieh Yu	A Low-Voltage Positive Buck-Boost Converter Using Average-Current-Controlled Techniques	It consists of one LC filter, ramp generator circuit, average-current-controlled circuit, and compensator network, active-current-sensing circuit, driving circuit, non-overlapping circuit and positive buck-boost converter including four power transistors.	Reduce some power management problems, such as size, cost, design complexity, simple compensation design, and EMI. The proposed low-voltage positive buck-boost converter using the active-current-sensing circuit and average-current-controlled techniques can work stably when the duty cycle is higher than 50% at 1MHz frequency.

Chin-Hong Chen, Chia-Ling Wei, and Kuo-Chun Wu	Integrated Non-Inverting Buck-Boost Dc-Dc Converter With Average-Current-Mode Control	Current-mode controller.	It can provide load current up to 300 mA. Therefore, it is suitable for portable electronic applications.
Juan Carlos Ostos Dylan Dah-Chuan Lu	Modeling And Analysis Of CCM Non-Isolated High Step-Up Interleaved Buck-Boost Dc/Dc Converters	The presented topology has two identical buck-boost converters connected in a parallel-input, series-output manner for boosting the output voltage.	An improved output voltage is reached by using this interleaved buck-boost topology instead of interleaved boost topology. Theoretically is infinity but practically looses limit this. This new topology can serve as an alternative to the typically used transformer isolated converter topology.

2.3 Buck-Boost Converter Topologies

The buck–boost converter is a type of DC-to-DC converter that has an output voltage magnitude that is either more than or less than the input voltage magnitude. Two different topologies are called *buck–boost converter*. Both of them can produce a range of output voltages, from an output voltage much larger (in absolute magnitude) than the input voltage, down to almost zero. There are many applications however, such as battery-powered systems, where the input voltage can vary widely, starting at full charge and gradually decreasing as the battery charge is used up. At full charge, where the battery voltage may be higher than actually needed by the circuit being powered, a buck regulator would be ideal to keep the supply voltage steady. However as the charge diminishes the input voltage falls below the level required by the circuit, and either the battery must be discarded or re-charged; at this point the ideal alternative would be the boost regulator

2.3.1 The inverting topology

The output voltage is of the opposite polarity than the input. This is a switched-mode power supply with a similar circuit topology to theboost converter and the buck converter. The output voltage is adjustable based on the duty cycle of the switching transistor. One possible drawback of this converter is that the switch does not have a terminal at ground; this complicates the driving circuitry. Neither drawback is of any consequence if the power supply is isolated from the load circuit (if, for example, the supply is a battery) because the supply and diode polarity can simply be reversed. The switch can be on either the ground side or the supply side.

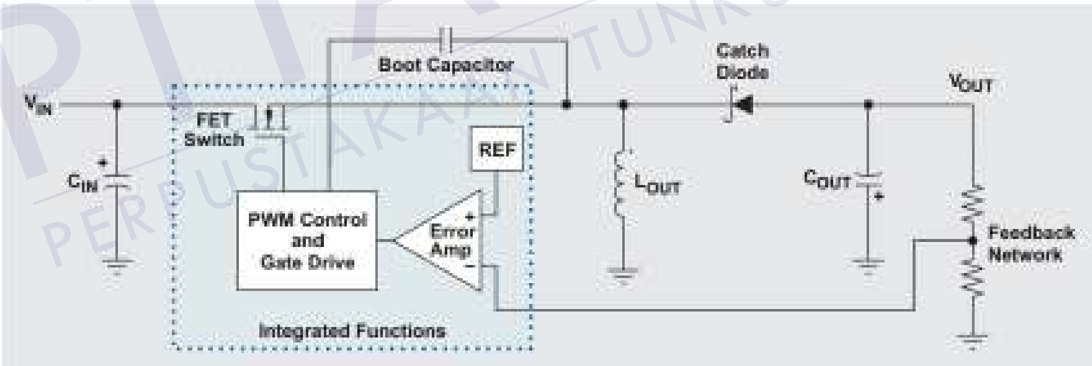

Figure 2.1: Non-Inverting Buck-Boost Topology.

During operation as shown in Figure 2.1, when the FET switch on, the voltage across the inductor is V_{in} and the current ramps up at a rate of $di/dt=V_{in}/L$. While the FET switch is on, the entire load current is supplied by energy stored in the output capacitor. When the FET switch turns off, the inductor conduct in reverses polarity to keep the inductor current continuous. The voltage across the inductor is approximately V_{out}, and the inductor current decreases as a rate of $di/dt=-V_{out}/L$.

During the off time, the inductor supplies current both to the load and to replenish the energy lost by the capacitor during the on time.

2.3.2 A buck (step-down) converter followed by a boost (step-up) converter

The output voltage is of the same polarity of the input, and can be lower or higher than the input. Such a non-inverting buck-boost converter may use a single inductor which is used for both the buck inductor and the boost inductor.

Like the buck and boost converters, the operation of the buck-boost is best understood in terms of the inductor's "reluctance" to allow rapid change in current. From the initial state in which nothing is charged and the switch is open, the current through the inductor is zero. When the switch is first closed, the blocking diode prevents current from flowing into the right hand side of the circuit, so it must all flow through the inductor. However, since the inductor does not like rapid current change, it will initially keep the current low by dropping most of the voltage provided by the source. Over time, the inductor will allow the current to increase slowly by decreasing its voltage drop. Also during this time, the inductor will store energy in the form of a magnetic field.

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